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MODELING TECHNIQUES FOR ANALYSIS OF STIFFENED SHELL STRUCTURES,--ETC(U)
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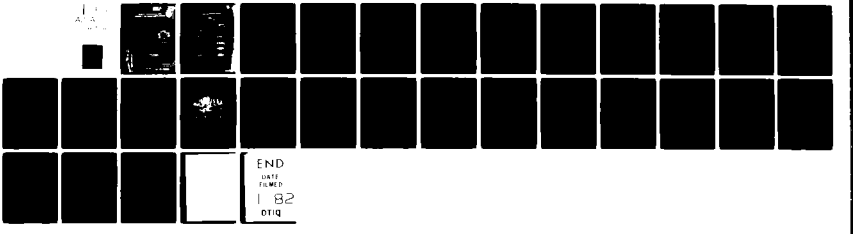

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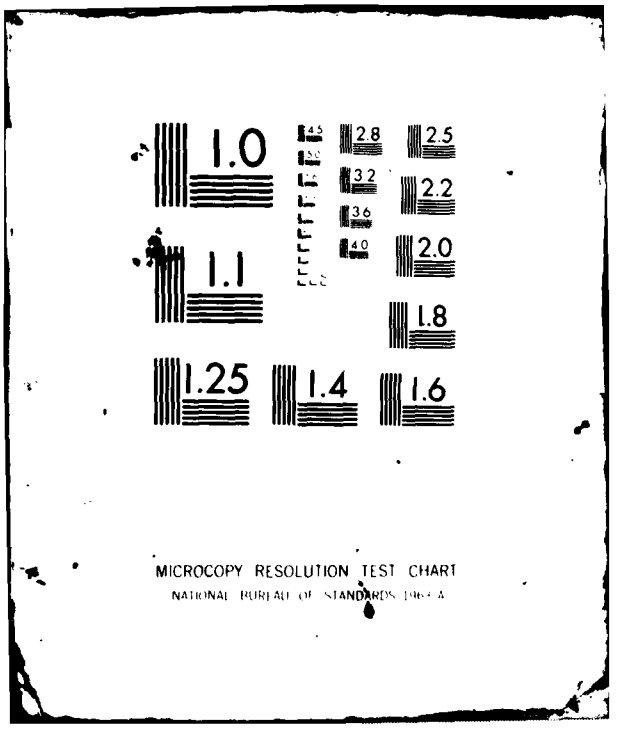
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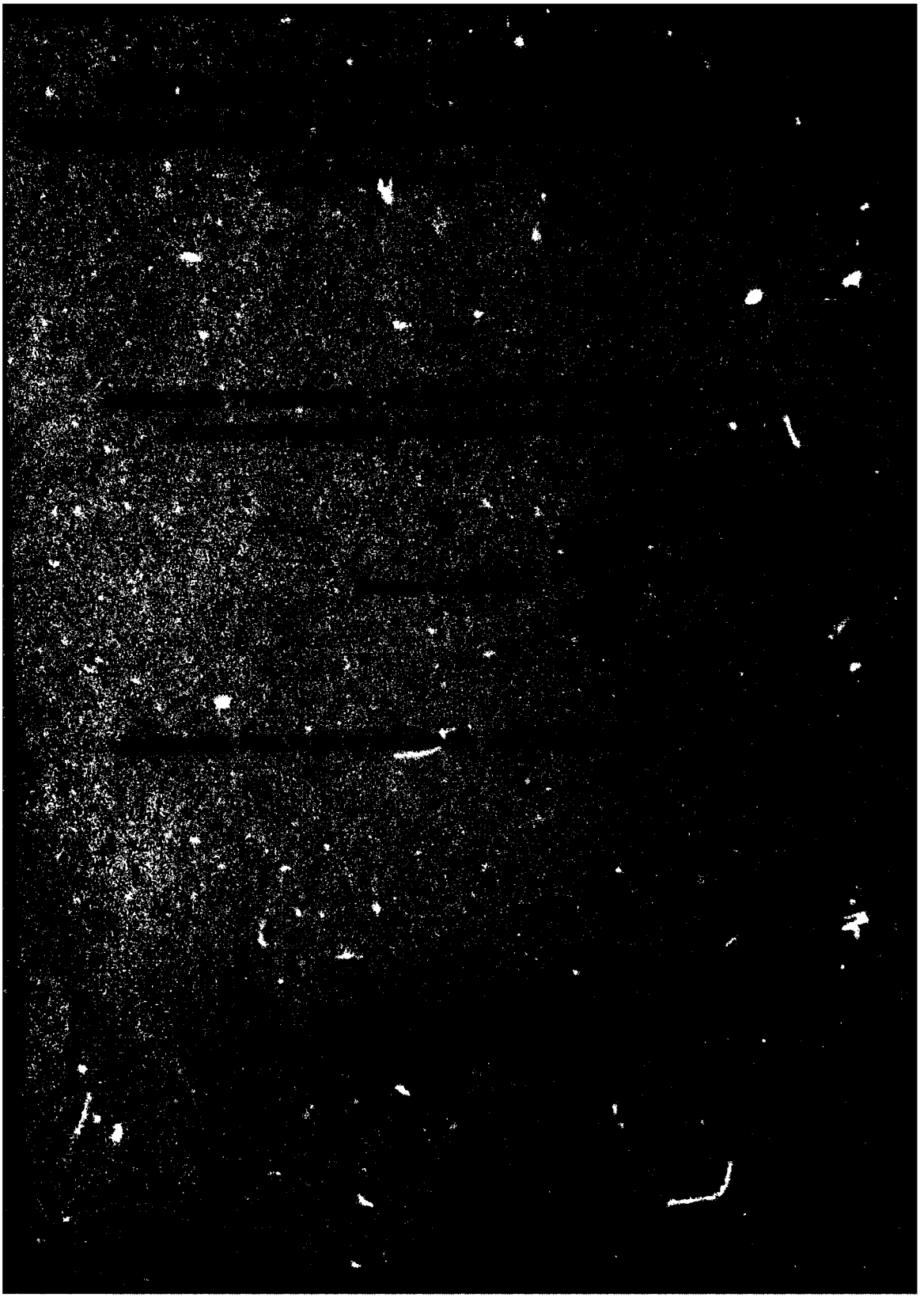

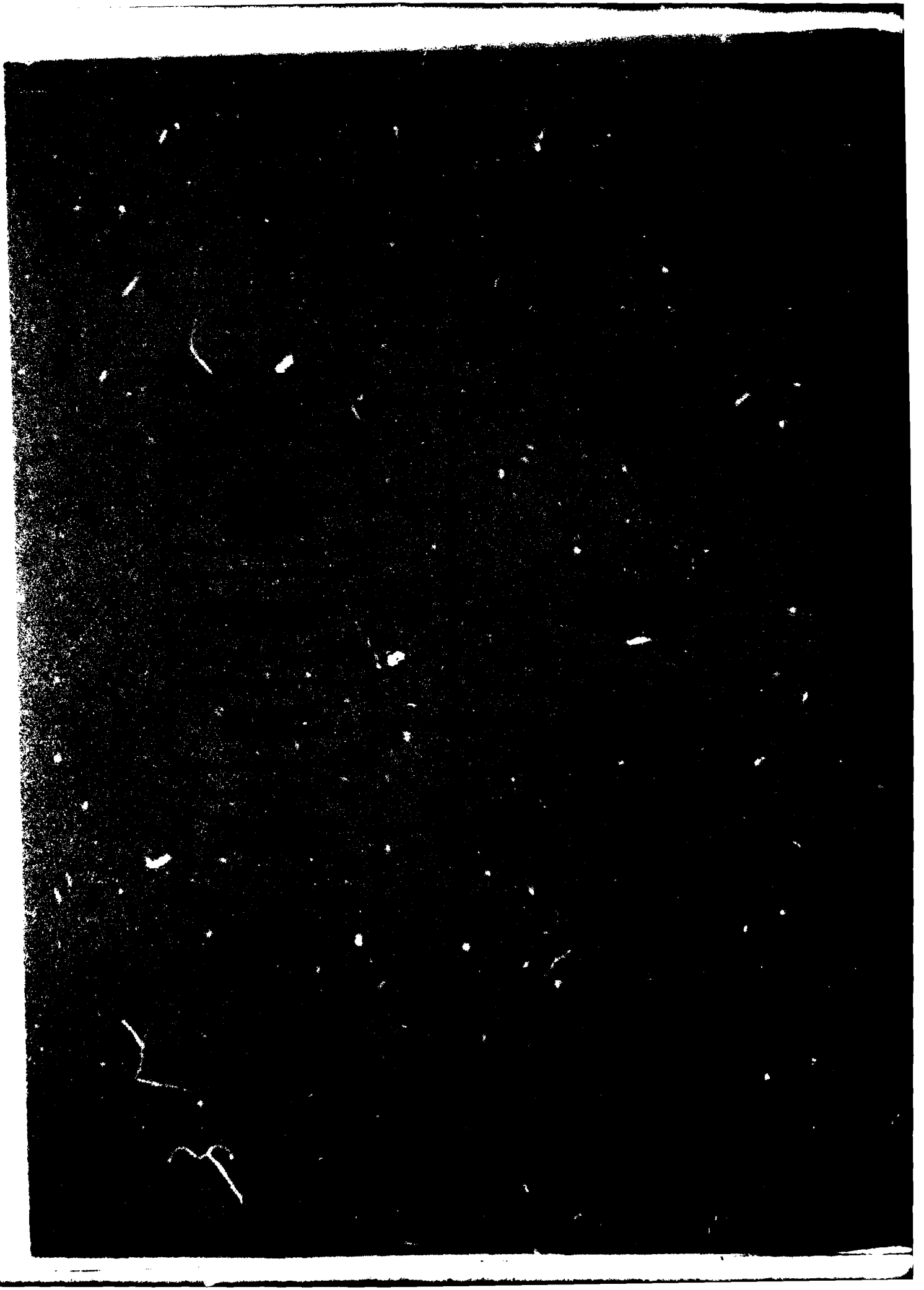

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The beam element available in computer program ADINA is inadequate for transient analysis of eccentrically stiffened shell structures, particularly when the lateral stability of the stiffener is of concern. As an alternative to modeling shell stiffeners with numerous continuum or transition elements, a stiffener modeling technique based on the multipoint constraint option in ADINA is presented. This technique leads to significant →

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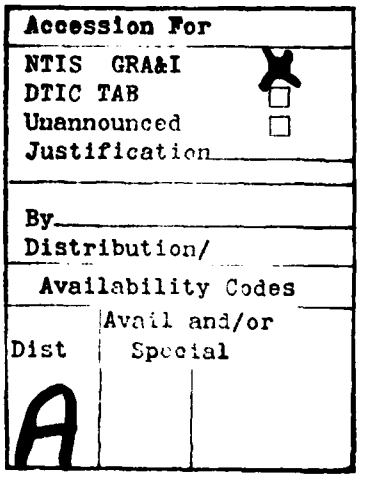
reductions in the number of elements and solution degrees of freedom needed for accurate stiffener modeling, yet allows inclusion in the analysis of effects of out-of-plane web distortion, longitudinal warping, and torsion. Stiffeners having various cross sectional geometries and boundary conditions have been modeled, and predicted response correlates well with experimental data. The approach is of practical significance for large stiffened shell problems, especially nonlinear analysis.

FOREWORD

Constrained-displacement, stiffener modeling techniques described in the report were developed for nonlinear structural analysis of stiffened shell structures, using finite element computer program ADINA. The formulation is general and can be effectively utilized with any general purpose program that provides a capability for user specification of displacement constraint equations.



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NOTATION

f_i	Concentrated forces
H	Stiffener height
p(x)	Distributed pressures
r,s,t	Local skewed coordinates
S	Stiffener frame spacing
t_f	Flange thickness
t_s	Shell plating thickness
t_w	Web thickness
u,v,w	Translational displacements
$\overline{V}_n$	Vector normal to plane of cross section
W	Width of flange
x,y,z	Global Cartesian coordinates
α,β	Rotational angles

ABSTRACT

The beam element available in computer program ADINA is inadequate for transient analysis of eccentrically stiffened shell structures, particularly when the lateral stability of the stiffener is of concern. As an alternative to modeling shell stiffeners with numerous continuum or transition elements, a stiffener modeling technique based on the multipoint constraint option in ADINA is presented. This technique leads to significant reductions in the number of elements and solution degrees of freedom needed for accurate stiffener modeling, yet allows inclusion in the analysis of effects of out-of-plane web distortion, longitudinal warping, and torsion. Stiffeners having various cross sectional geometries and boundary conditions have been modeled, and predicted response correlates well with experimental data. The approach is of practical significance for large stiffened shell problems, especially nonlinear analysis.

ADMINISTRATIVE INFORMATION

The work described in this report was funded by the Naval Sea Systems Command (SEA 3221) and was performed under David W. Taylor Naval Ship Research and Development Center Program Element Submarine Combat Protection, Task Area SF 434 00 001 and Work Unit 1750-294.

INTRODUCTION

Transient analysis of eccentrically stiffened, shell structures can be quite complex. Under severe loading conditions such as impacts or blast waves, shell stiffeners can become laterally unstable. Lateral instability of a stiffener leads to a sudden loss of strength of transverse sections and can result in catastrophic structural failure. The significance of lateral instability of stiffeners as a primary mode of structural failure is indicated in Figure 1.

Combinations of inplane and lateral loading can produce significant out-of-plane deformations in a shell stiffener. Unfortunately, lateral instability of stiffeners caused by dynamic loading is poorly understood. As pointed out by Adamchak,[1*] the primary difficulty encountered in attempts to analyze lateral behavior of shell stiffeners is the inability to properly account for web deformations or to adequately model complex, higher order, out-of-plane modal displacement patterns. To include the effects of these phenomena in a general, nonprismatic "beam" element would be a formidable task and is probably beyond the scope of the state of the art of finite element technology. As an example, the three-dimensional

*A complete listing of references is given on page 21.

beam element in ADINA (a finite element program for automatic dynamic incremental nonlinear analysis)[2,3] assumes a prismatic cross section with no centroidal offsets. Although the beam element of ADINA does provide torsional stiffness about the principal axis, it cannot account for out-of-plane deformation and warping of the cross section. An improved isoparametric curved beam element has been formulated by Bathe and Bolourchi.[4] This element is fully compatible with both the three-dimensional and thin-shell elements.* Unfortunately, it lacks the needed generality for modeling arbitrary stiffener geometries and out-of-plane deformation of the cross section.

An alternate modeling strategy that can overcome previously enumerated difficulties is to fully model the stiffener as an assemblage of continuum or thin-shell elements. Unfortunately for arbitrary stiffener geometries, such an approach can require numerous elements and excessive degrees of freedom for accurate modeling.

In this report, a constrained-displacement modeling technique is presented. The ADINA displacement constraint option, together with three-dimensional solid or thin-shell elements, is used to model shell stiffeners of arbitrary geometry. The number of elements and solution degrees of freedom can be substantially reduced, even though effects of out-of-plane deformations are retained in the analysis.

STIFFENER DEFORMATION UNDER COMBINED LOADINGS

The deformed geometry of a flexible shell stiffener under the action of in-plane and lateral loading is shown in Figure 2. Lateral deformations can be characterized as a combination of

1. Out-of-plane bending and distortion of the stiffener (u,v)
2. Longitudinal warping or twisting of the cross section (angle β)
3. Rotation and bending of the shell plating to which the stiffener is attached (angle α).

This report is mainly concerned with curved shell structures and combinations of asymmetric distributed pressures p(x) and eccentric concentrated forces f_i (Figure 3) which load the stiffener primarily in transverse compression and torsion. These loads pose the most significant threat to lateral stability of the stiffener because they tend to lessen transverse and torsional resistance of the stiffened shell

*It is understood that the isoparametric, curved beam element will be available in the 1981 release of ADINA.

section and, also, cause the stiffener to distort away from the stable equilibrium configuration. Consequently, an adequate model of a stiffened shell with arbitrary cross section geometry should include sufficient detail--node and gaussian-integration points--to map complex lateral distortion patterns as well as to account for large gradients in the stress and strain fields.

CONSTRAINED-DISPLACEMENT STIFFENER MODEL

Some examples of finite element modeling for flexible shell stiffeners are shown in Figure 4. The continuum element model is fully compatible. In contrast, the ADINA isoparametric, thin-shell element formulation allows only five degrees of freedom--three translations and two rotations--at a node and requires the midsurface normal vector $\overline{V}_n$ to be specified at each midsurface node. This requirement leads to a discontinuity at shell intersections which must be resolved to prevent a singular stiffness matrix. In Reference 2, it is suggested that such discontinuities can be overcome with constraint equations of the type indicated in Figure 5. It is proposed herein that the ADINA linear, multipoint displacement constraint option be used in a more general fashion to overcome the previously outlined difficulties and, also, to reduce the number of elements and solution degrees of freedom required for more effective analysis when a continuum element model is preferred.

In ADINA, linear, multipoint displacement constraint equations have the general form

$$u_{ij} = \sum_{k=1}^{N} a_k \, u_{mn} \tag{1}$$

where k = 1, 2, 3...N

$1 \leq m \leq$ NUMNP (number of node points)

n = 1, 2, or 3

In Equation (1), n is the number of independent translational or rotational degrees of freedom, a_k are weighting factors, and u_{ij} is the displacement or rotational degree of freedom at the i th node point in or about the j th direction or axis.

If a master-slave nodal dependency is established for common nodes at intersections of shell and stiffener or web and flange, then stiffened shell sections (Figure 6) can be easily modeled. Development of suitable constraint equations for the dependent degrees of freedom is straightforward. As an example, consider the continuum element model in Figure 7. To a first order approximation, the angle of rotation of the intersection of shell and stiffener about the normal to the cross sectional plane is defined as

$$\alpha_z = \frac{v_4 - v_3}{t_s} \tag{2}$$

and u, v, and w are components of displacement in the x, y, and z or r, s, and t coordinate directions. If it is assumed that the angle of intersection remains constant during deformation, then the dependent degrees of freedom become

$$u_1 = u_3 + \frac{t_w}{2}\alpha_z = u_3 - a_o v_3 + a_o v_4 \tag{3}$$

$$v_1 = v_3 \tag{4}$$

$$w_1 = w_3 \tag{5}$$

$$u_2 = u_3 - \frac{t_w}{2}\alpha_z = u_3 + a_o v_3 - a_o v_4 \tag{6}$$

$$v_2 = v_3 \tag{7}$$

$$w_2 = w_3 \tag{8}$$

where $a_o = \frac{1}{2}\left(\frac{t_w}{t_s}\right)$ (9)

Equations (3)-(9) are valid in either global Cartesian or local skewed coordinate reference systems as long as the normal to the cross sectional plane is in the direction of a principal axis because displacements of interest will always lie in a principal plane. If, however, the normal does not coincide with a principal direction, for example, for a curved shell for which displacements are calculated in terms of global Cartesian coordinates (Figure 8), the components of the rotational displacement in the principal directions are obtained with a simple transformation. For such cases, the angle of rotation about the normal is defined as

$$\alpha_t = \frac{v_4 - v_3}{t_s} \tag{10}$$

and the increment of displacement due to this rotation becomes

$$\Delta r = \frac{t_w}{2} \alpha_t = \frac{1}{2} \left(\frac{t_w}{t_s} \right) (v_4 - v_3) \tag{11}$$

The components of displacement in the principal directions are

$$\Delta x = \sin \theta \, \Delta r \tag{12}$$

$$\Delta z = \cos \theta \, \Delta r \tag{13}$$

and constraint equations for the dependent degrees of freedom become

$$u_1 = u_3 + \Delta x = u_3 - a_1 v_3 + a_1 v_4 \tag{14}$$

$$v_1 = v_3 \tag{15}$$

$$w_1 = w_3 + \Delta z = w_3 + a_2 v_3 - a_2 v_4 \tag{16}$$

$$u_2 = u_3 - \Delta x = u_3 + a_1 v_3 - a_1 v_4 \tag{17}$$

$$v_2 = v_3 \tag{18}$$

$$w_2 = w_3 - \Delta z = w_3 - a_2 v_3 + a_2 v_4 \tag{19}$$

where $a_1 = \frac{1}{2}\left(\frac{t_w}{t_s}\right) \sin \theta$ (20)

$$a_2 = \frac{1}{2}\left(\frac{t_w}{t_s}\right) \cos \theta \tag{21}$$

EXAMPLE: LATERAL STABILITY OF A STIFFENER UNDER IMPACT LOADING

The constrained-displacement modeling technique was used to investigate the stiffener lateral stability of a stiffened cylindrical shell subjected to a known impact loading. Figure 9 shows the shell geometry and loading conditions. Figure 10 shows the corresponding ADINA finite element model. Three-dimensional continuum elements were used to model both the shell plating and the stiffeners. Only one T-stiffener was fully modeled. The other was modeled as a dynamically equivalent bar stiffener. A 90-degree sector of the shell was modeled with symmetry imposed on nodal displacements along the longitudinal boundaries. Transverse boundaries were modeled as pinned supports. Displacement constraints were imposed at intersections of shell and stiffener and web and flange.

In Figure 11, predicted radial response of the T-stiffener is compared to experimentally measured response data. Correlation between the two is quite good. Lateral response of the flange is shown in Figure 12. The higher order modal displacement pattern, characteristic of out-of-plane stiffener deformation, is clearly indicated. In the study, it was observed that the peak lateral response of the frame was 30 percent of the peak radial response, and peak stresses in the flange were comparable to peak stresses in the hull plating in the vicinity of the impact point. In contrast, the bar stiffener model imparted a higher degree of torsional resistance to the shell plating and grossly underpredicted the stiffener stresses.

These results demonstrate the accuracy of the constrained-displacement modeling technique and provide insight into the practical significance of out-of-plane stiffener deformations.

CONCLUSIONS

A constrained-displacement modeling technique for eccentrically stiffened shell structures has been presented which allows the effects of out-of-plane deformations of the stiffener to be included in an analysis. For the transient analysis of an impulsively loaded shell structure, predicted response correlates well with experimentally measured data. This technique overcomes the difficulties encountered by using generalized beam elements while minimizing the number of continuum elements and solution degrees of freedom required for accurate stiffener modeling.

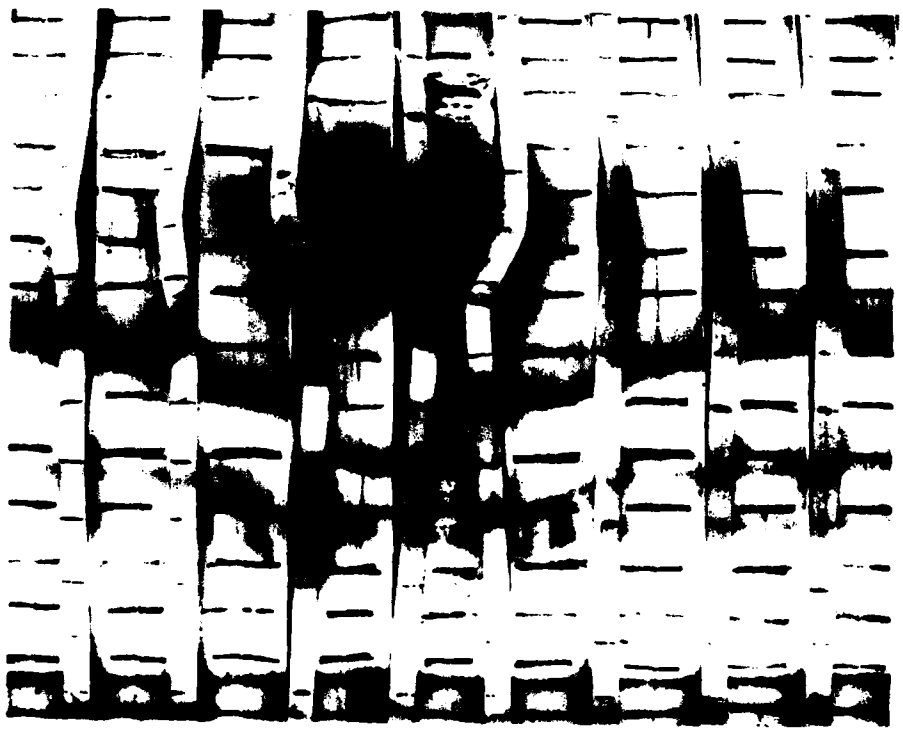


Figure 1 - Example of Stiffener Lateral Instability

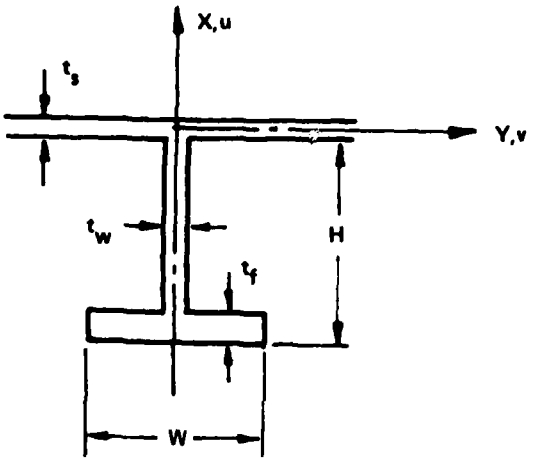


Figure 2a - Undeformed Geometry

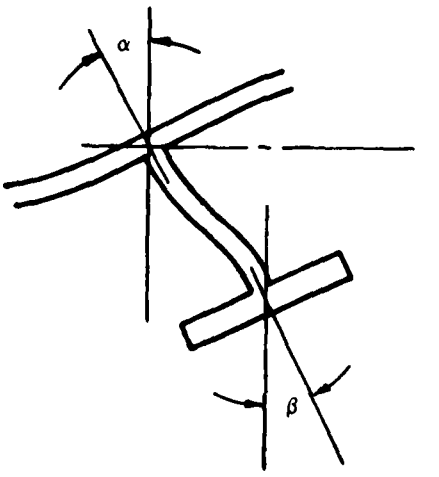


Figure 2b - Deformed Geometry

Figure 2 - Stiffener Deformations under Combined Loading

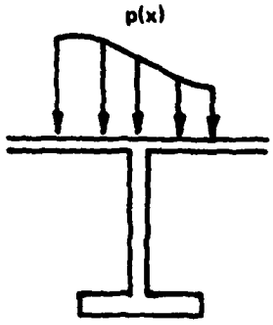


Figure 3a - Asymmetric Pressures

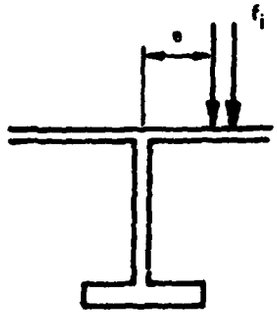


Figure 3b - Eccentric Forces

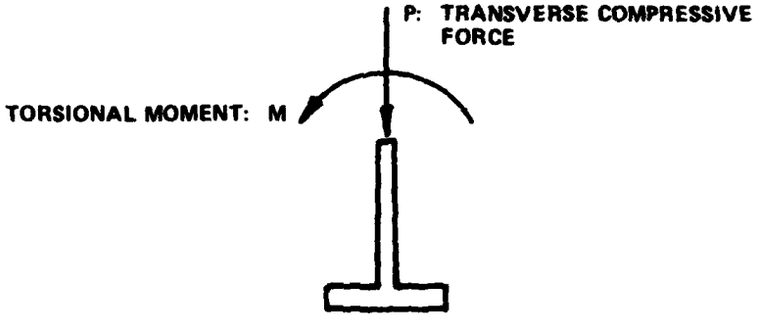


Figure 3c - Equivalent Stiffener Loads

Figure 3 - Significant Shell Stiffener Loading

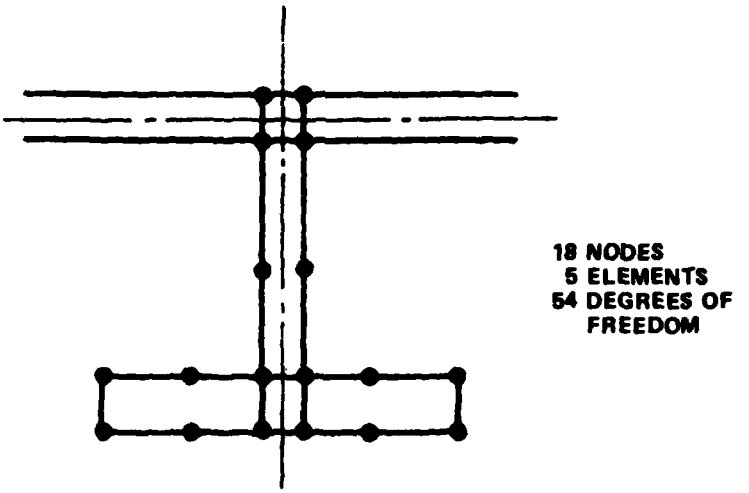


Figure 4a - Continuum Model

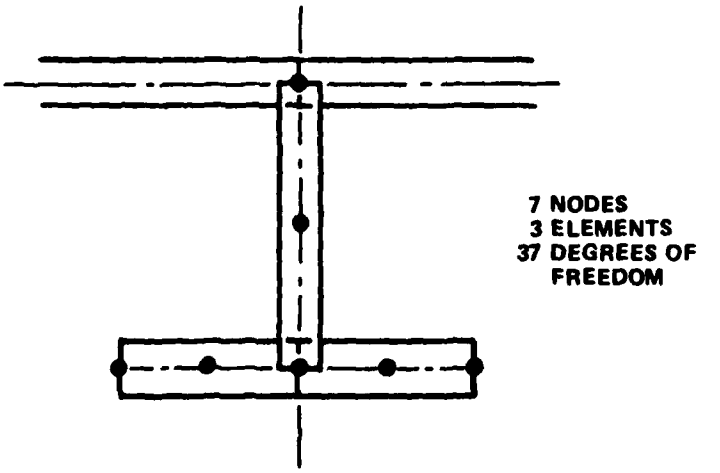


Figure 4b - Thin Shell Model

Figure 4 - Stiffener Modeling Techniques

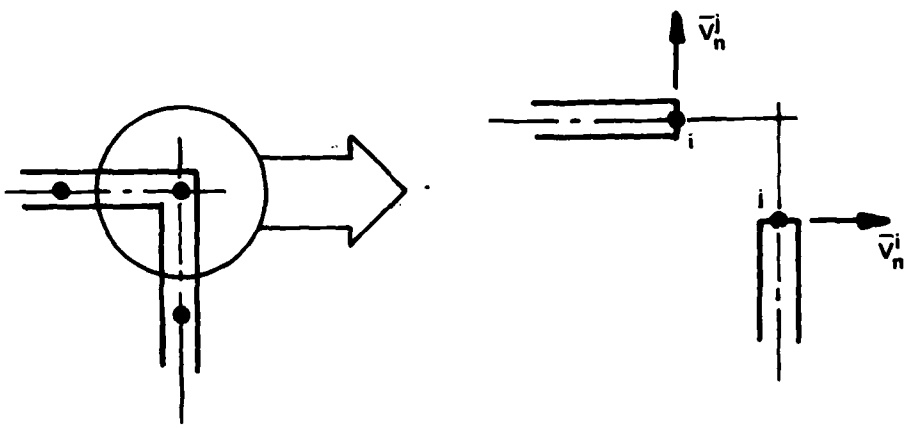


Figure 5 - Modeling Techniques for Shell Intersections

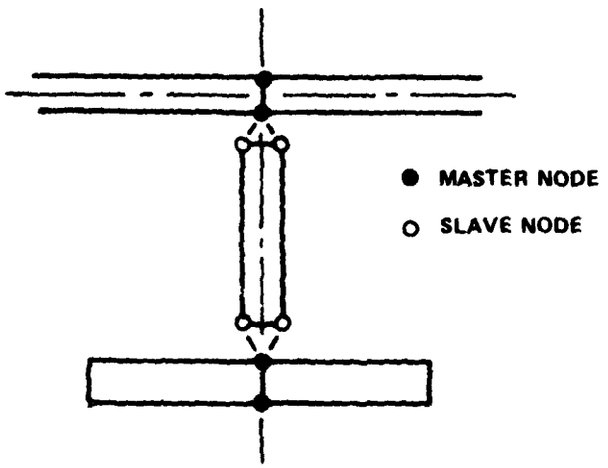


Figure 6a - Continuum Model

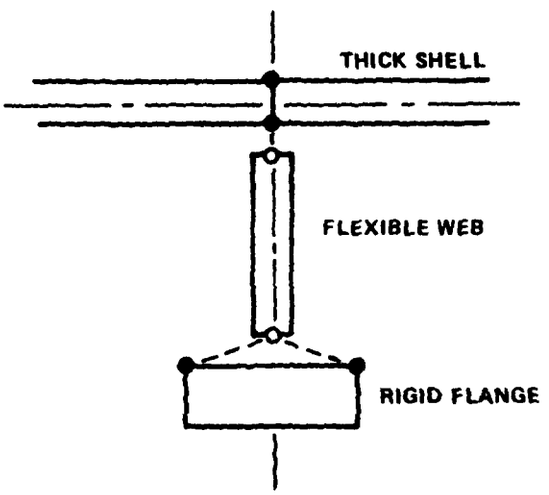


Figure 6b - Hybrid Model

Figure 6 - Constrained-Displacement Stiffener Models

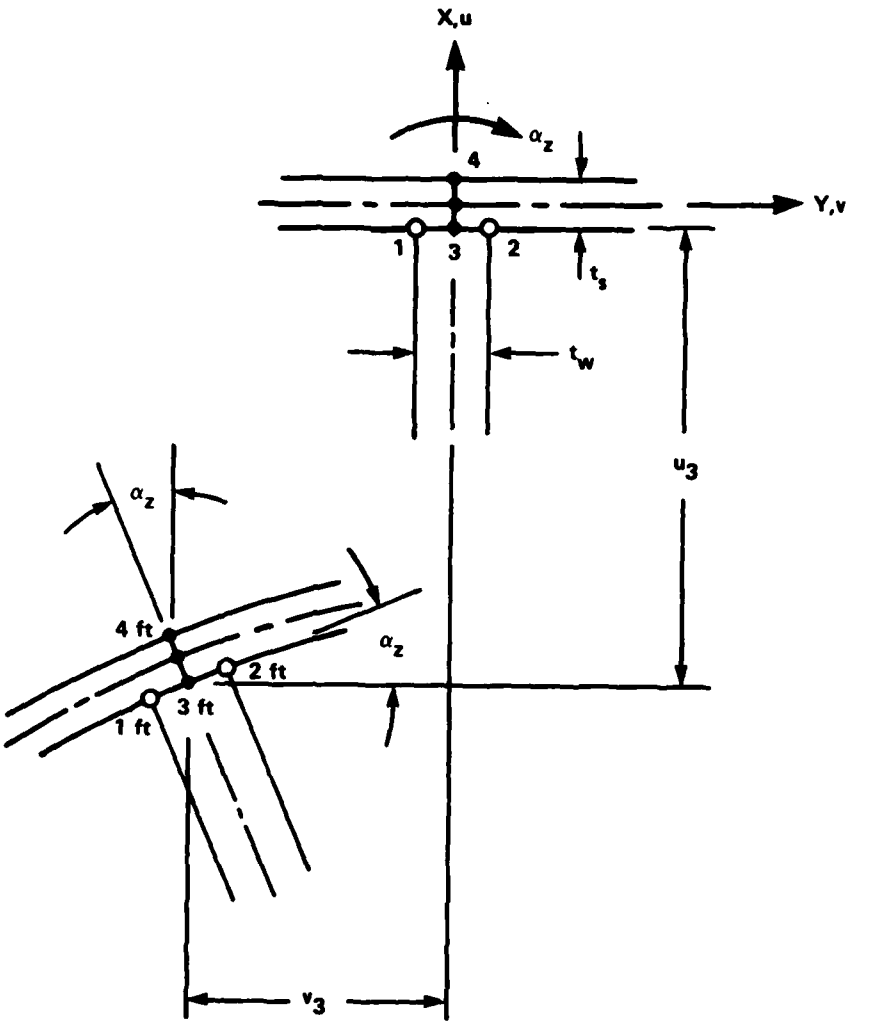


Figure 7 - Deformations at a Shell Stiffener Intersection

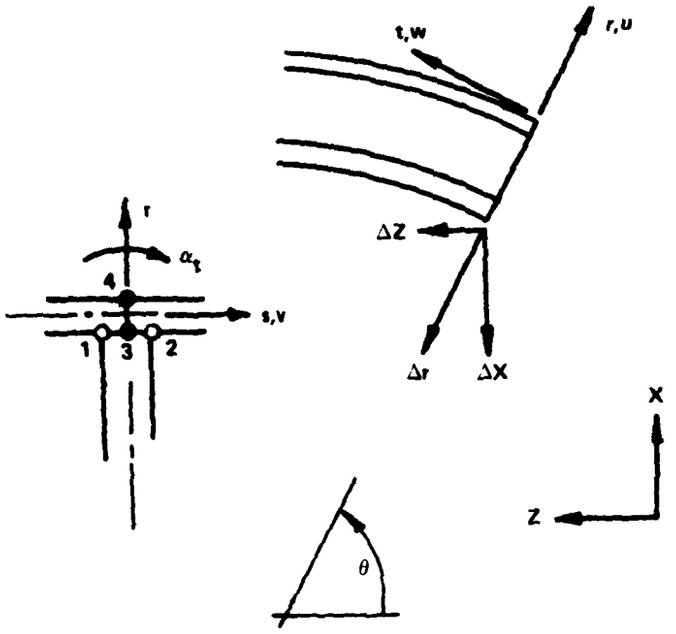
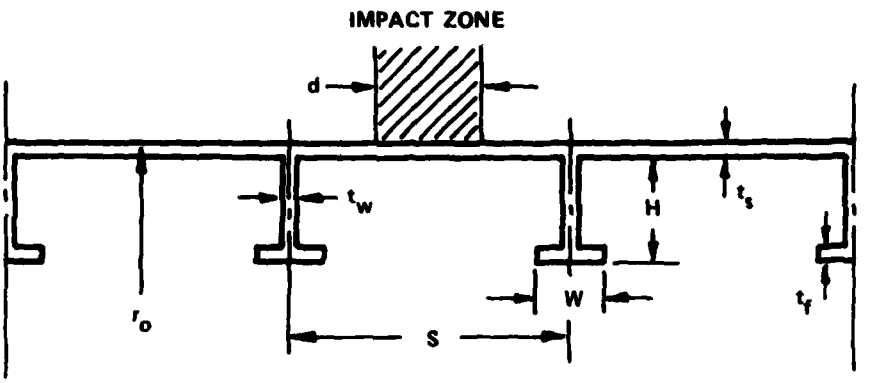


Figure 8 - Global Components of Rotational Displacement



$$\frac{t_s}{r_o} = 0.01 \quad \frac{t_w}{t_s} = 0.53 \quad \frac{t_f}{t_s} = 0.93 \quad \frac{H}{r_o} = 0.06$$

$$\frac{S}{r_o} = 0.17 \quad \frac{d}{S} = 0.64 \quad \frac{H}{W} = 1.33$$

Figure 9a - Shell Geometry

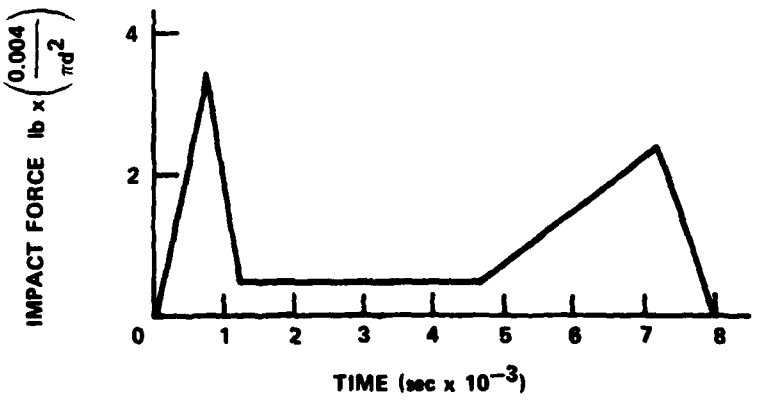


Figure 9b - Impact Loading

Figure 9 - Stiffened Cylindrical Shell under Impact Loading

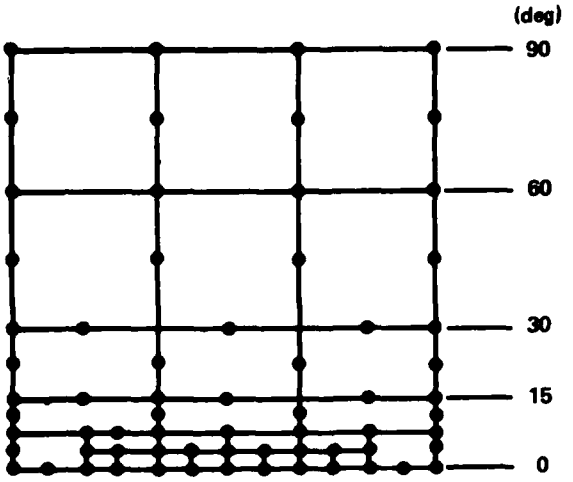


Figure 10a - Shell Plating Mesh

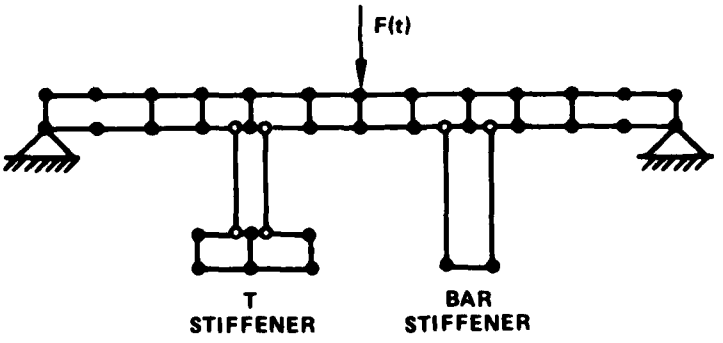


Figure 10b - Stiffener Modeling

Figure 10 - Model for ADINA Analysis of Stiffener Lateral Stability

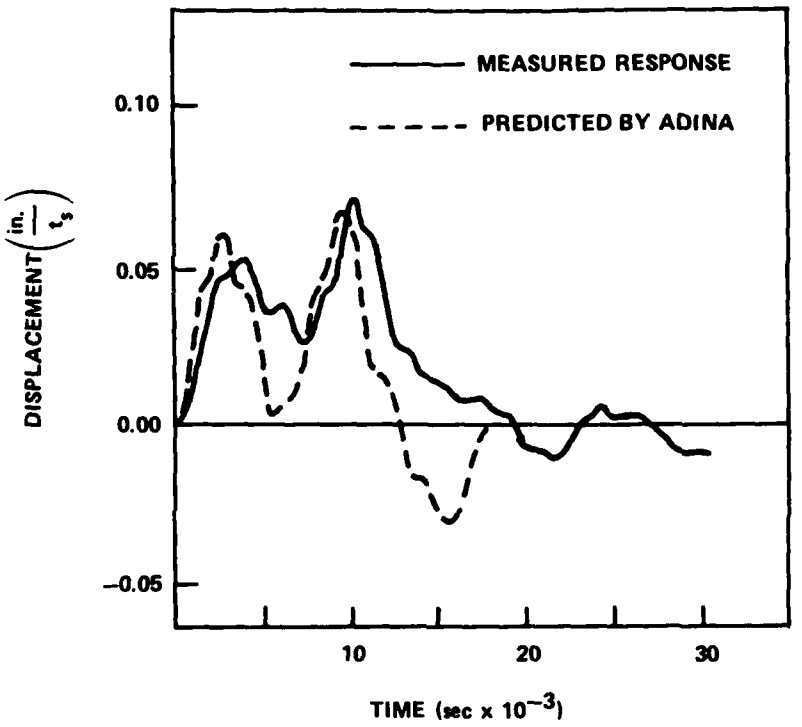


Figure 11 - Radial Response of Stiffener

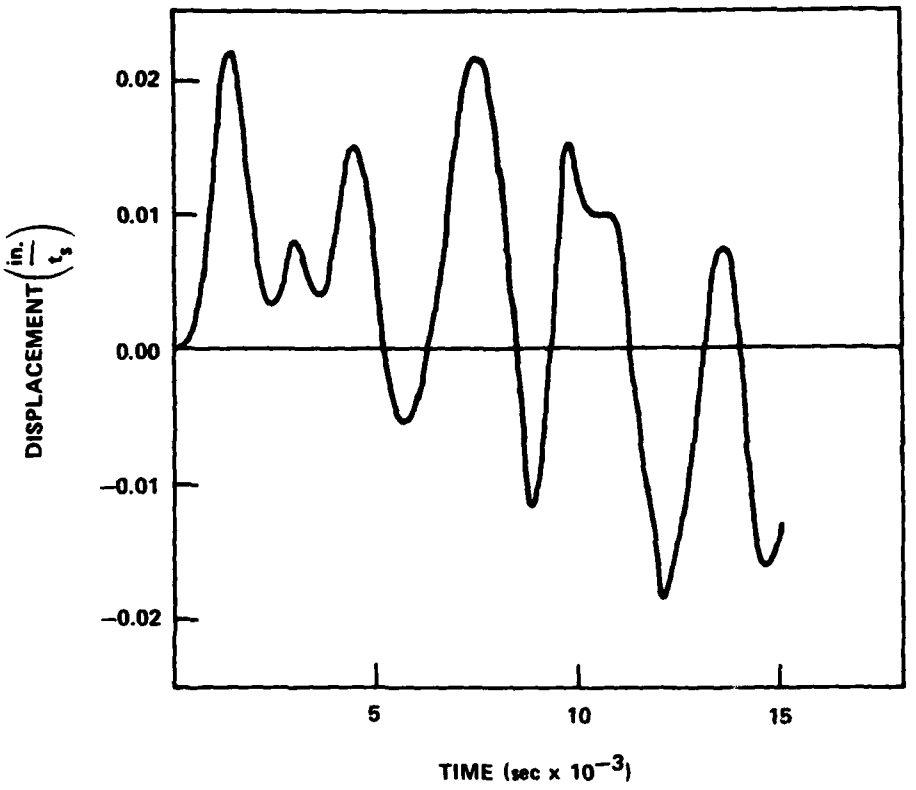


Figure 12a - Response Predicted by ADINA

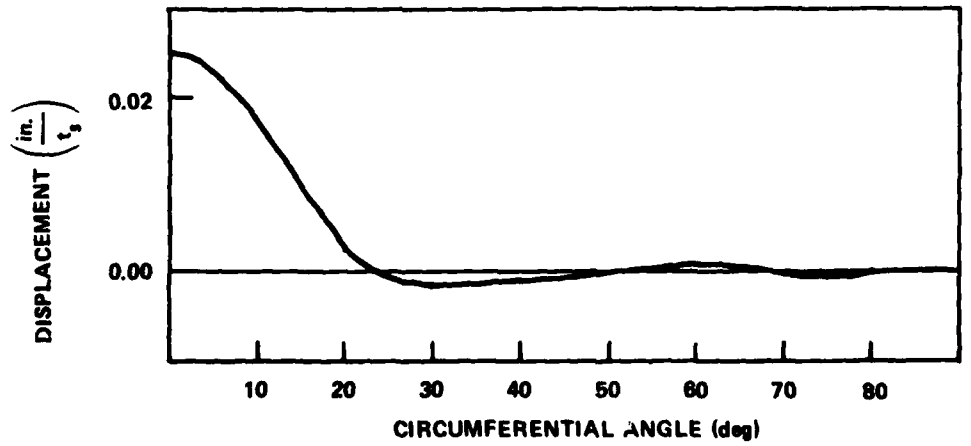


Figure 12b - Peak Displacement Contour

Figure 12 - Lateral Response of Stiffener

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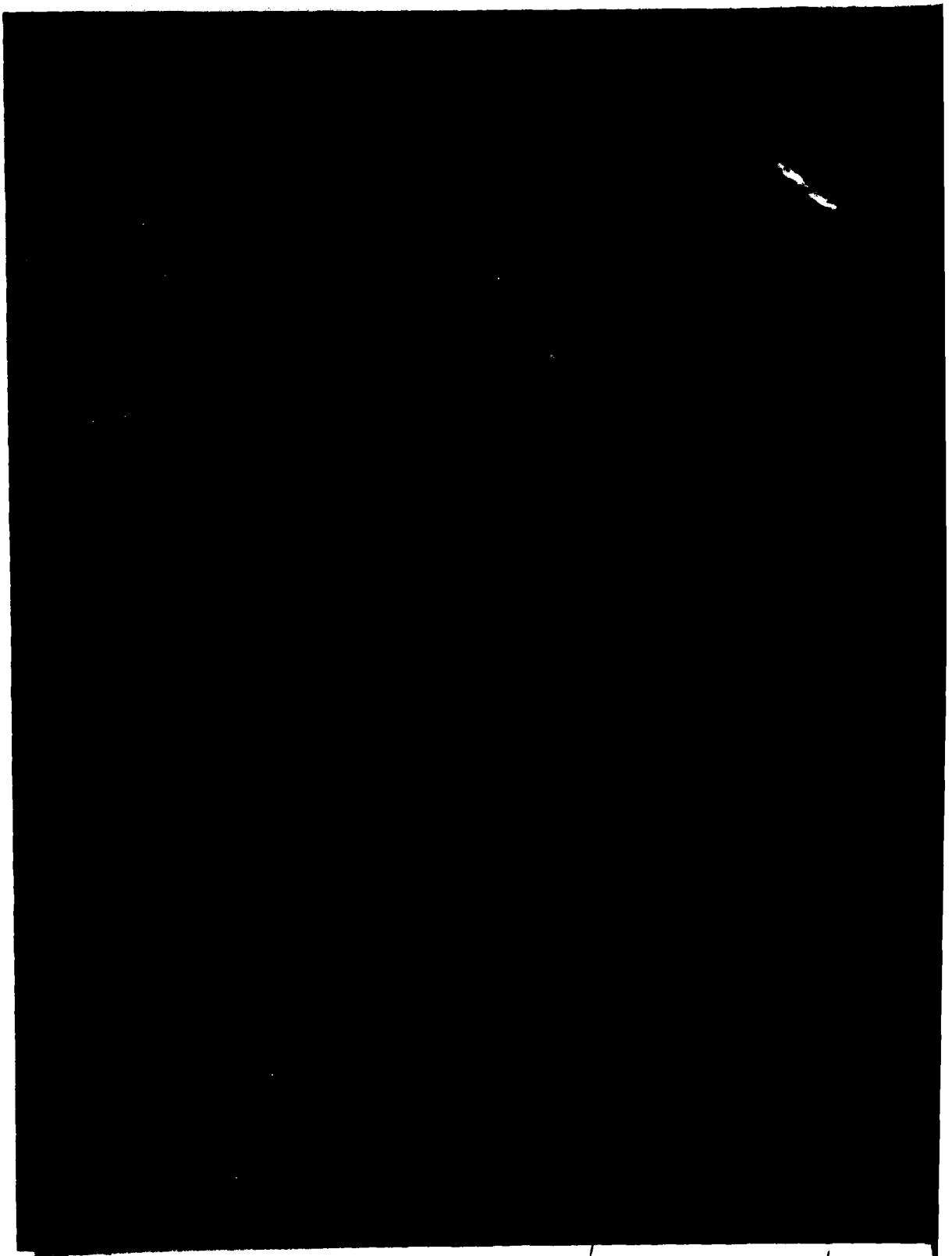

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